REPORT DOCUMENTATION PAGE		Form Approved	

Public reporting burden for this collection of information is estimated to average 1 hou ... instructions, searching existing data sources, gathering and maintaining the data needed ... information. Send comments regarding this burden estimate or any other aspect of this ... for reducing this burden to Washington Headquarters Services, Directorate for Informa ... Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Manager. ... (0704-0188), Washington, DC 20503

AFRL-SR-AR-TR-04-

0439

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 29 July 2004	3. REPORT TYPE AND DATES COVERED final report, 1 May 2001 - 30 June 2004	
4. TITLE AND SUBTITLE Adaptive Learning Across Task Environments		**5. FUNDING NUMBERS** F49620-01-1-0295	
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Bradley C. Love The University of Texas at Austin 1 University Station A8000 Austin, TX 78712-0187		**8. PERFORMING ORGANIZATION REPORT NUMBER** F49620-01-1-0295	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research AFOSR/NL Program Manager: Perception & Cognition Program (att: Dr. Robert D. Sorkin) 4015 Wilson Blvd., Rm. 713 Arlington VA 22203-1954		**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**	

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unlimited

20040901 095

13. ABSTRACT *(Maximum 200 Words)*

The major accomplishment of this project was increasing the range of situations in which experimental results and models are informative for making predictions about how to best train personnel. In concert with a series of empirical investigations, the SUSTAIN (Supervised and Unsupervised STratified Adaptive Incremental Network) model of how humans learn categories from examples was developed. SUSTAIN initially assumes a simple category structure. If simple solutions prove inadequate and SUSTAIN is confronted with a surprising event (e.g., it is told that a bat is a mammal instead of a bird), SUSTAIN recruits an additional cluster to represent the surprising event. Newly recruited clusters are available to explain future events and can themselves evolve into prototypes–attractors–rules. SUSTAIN's discovery of category substructure is affected not only by the structure of the world but by the nature of the learning task and the learner's goals. SUSTAIN successfully extends category learning models to studies of inference learning, unsupervised learning, category construction, and contexts in which identification learning is faster than classification learning. SUSTAIN brings the field closer to making a priori predictions about learning and performance under a variety of conditions.

14. SUBJECT TERMS cognitive modeling, behavioral research, training, learning			**15. NUMBER OF PAGES** 8
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	**18. SECURITY CLASSIFICATION OF THIS PAGE** UNCLASSIFIED	**19. SECURITY CLASSIFICATION OF ABSTRACT** UNCLASSIFIED	**20. LIMITATION OF ABSTRACT** Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

Final Performance Report
1 May 2001 - 30 June 2004
AFOSR Grant #F49620-01-1-0295

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Objectives:

The primary objective of the project was to develop theories and computational models of human category learning that are applicable across a broad range of situations. The project expanded to considering the determinants of recognition memory and how people align structured representations. These efforts were necessary to bridge the gap between behavioral research and more realistic training and performance situations. A secondary goal of the project was to develop effective machine learning models by adapting models intended to replicate aspects of human information processing.

Status of Effort:

Dr. Bradley Love's overall lab effort has been oriented to satisfy the objectives of this project. In addition to the PI, Ph.D. students John Dennis, Todd Gureckis, Levi Larkey, and Yasuaki Sakamoto have contributed to the project. Postdoctoral researcher Matthew Jones has also contributed in the final year of the project. The aforementioned personnel were engaged in data collection, modeling of results, and the dissemination of results through conference presentations and journal publications.

By leveraging additional sources of funding, such as internal grants from the University of Texas, an NRSA fellowship to Mathew Jones, and an NDSEG fellowship to Levi Larkey, the laboratory has been able to exceed the stated objectives of the original proposal and have laid the groundwork for a more ambitious project that is currently being undertaken and is funded by AFOSR.

Accomplishments/New Findings:

At the inception of this project the vast majority of behavioral research and modeling in category learning focused on a single task, namely classification learning. In classification learning, the learning is presented with a stimulus, classifies it, and receives corrective feedback. While worthy of study, there are clearly many other ways humans learn and apply knowledge. Unfortunately, these other modes of learning are poorly understood and largely unexplored. The major accomplishment of this project was expanding the range of situations in which experimental results and models are relevant. Beyond academic interest, such an endeavor is necessary to develop models that can make a priori predictions about how to best train personnel.

On the empirical front, Bradley Love has developed a technique for comparing supervised and unsupervised learning performance (Love, 2002). This technique revealed that findings in supervised classification learning (e.g., an advantage for learning compact nonlinear category structures over linear inter-correlated family resemblance structures) do not extend to unsupervised learning, particularly unsupervised learning under incidental learning conditions (as opposed to intentional learning conditions). Love (2003) demonstrated the importance of properly pairing the induction task with the learning problem (i.e., category structure) in a series of tasks.

Yamauchi, Love, and Markman (2002) explored differences between inference learning (i.e., learning by inferring missing properties of an object from a known category and then receiving corrective feedback) and classification learning (i.e., predicting the category membership of an object and then receiving corrective feedback). Yamauchi, Love, and Markman (2002) found that inference learning promotes a focus on the internal structure of each individual category whereas classification learning leads to encoding of information that discriminates between categories.

Sakamoto and Love (in press) have conducted a series of studies exploring the role of errors in developing memories and how category structure influences what is later recognized. Sakamoto and Love found that learning errors only lead to improved recognition when the errors highlight the underlying structure of the categories. The findings have been modeled by existing approaches and disconfirm rule and exemplar models. Interestingly, even when people consciously apply a rule, the performance data are more consistent with a cluster-based than a rule-based approach.

These and other studies have been instrumental in the development of the SUSTAIN model (Love, Medin, & Gureckis, 2004). SUSTAIN represents categories by one or more clusters. SUSTAIN is now the leading model of learning across induction tasks (e.g., classification, inference, and unsupervised learning). The key difference between SUSTAIN and other models is that it strikes a balance between uncovering the structure in the world and the structures dictated by a learner's goals by assuming categories have a simple structure and incrementally adding complexity as needed to satisfy the learner's goals. Thus, the category structures that SUSTAIN acquires are governed by both the structure of the world and the current task or goal. Forming cluster representations in this way (which span exemplar, prototype, and rule-based approaches), seems to be the key to modeling the flexibility people show in learning. SUSTAIN's success in addressing performance across a range of interactions and learning paradigms is a critical step toward developing models that are applicable to realistic training situations.

SUSTAIN has also proved useful in understanding developmental and aging trends. Gureckis and Love (2004) applied data to infant correlation learning data and have successfully captured the developmental trends, relating these trends to the development of the hippocampus. Current work applies this same line of explanation to understanding learning and recognition data from amnesiacs.

Gureckis and Love (2003) have developed a version of SUSTAIN that unifies unsupervised and supervised learning through a common cluster recruitment mechanism. The fits of the modified SUSTAIN (named uSUSTAIN) were encouraging across a range of tasks. One of the primary objectives of the SUSTAIN project is to unify a range of induction tasks in a common framework.

The previously mentioned work has been instrumental in hastening the development of SUSTAIN's successor. A preliminary version of the new model, CLUSTer Error Reduction (CLUSTER), has been coded and the initial results are promising. Some pilot simulations were presented at the McDonnell Foundation's Cognitive Neuroscience of

Category Learning meeting. The model places all learning and recognition in an auto-associative error-reduction framework. The formulation of the error term varies depending on the current goals and directs cluster formation. CLUSTER's elegant formalism should make it easier to interface it with other systems. One line of research is interfacing CLUSTER with dialogues or hints in order to model direct instruction and how it interacts with learning from examples. CLUSTER can easily move from supervised to unsupervised learning within a single learning episode. Beyond helping to understand the nature of human learning, CLUSTER may prove useful as a machine learning system. Developing CLUSTER is now Bradley Love's laboratory's primary effort. Already, CLUSTER has opened up exciting possibilities. Matt Jones and Bradley Love have discovered that CLUSTER's learning rules can be trivially modified using Q-Learning so that CLUSTER is applicable to reinforcement learning situations. Reinforcement learning supports complex skill learning that involves multiple actions and continuous feedback that is dependent on previous actions. One example of such a situation is learning to keep an aircraft stable.

Additional personnel funded through other sources have allowed the scope of the project to extend to considering more complex representations. Work in category learning currently focuses on situations in which stimuli are represented by features or locations in a multi-dimensional space. Humans often employ more complex representations that utilize relations (e.g., cause/effect, spatial relations, part-of, attracts, attacks, etc.).

Developing theories and models of how people process these predicate structures is a daunting task. Unfortunately, recent results from Love and Markman (2003) argue that this difficult task will have to be addressed. Love and Markman (2003) found that even the canonical cases in which stimulus dimensions (e.g., size, shape, and color) appear independent (e.g., they are recoverable from MDS procedures and do not show substantial Garner interference), dimensions appear to be quantified over one another (e.g., large(triangle) as opposed to large and triangle).

Another example of the importance of relations in how we conceptualize situations comes from Jones and Love (in preparation; 2004). They explored how word usage patterns affect meaning. The work makes contact with existing corpus-based approaches, but goes beyond the "bag of words" approaches by considering the structural role a word plays. Words or concepts that play similar roles may become more similar. For example, if a ball is kicked and a can is kicked (both objects play the role of being kicked), then these words may become more similar. This work may eventually lead to more effective text processing systems, as well as category learning systems that leverage information that is currently being discarded.

As a first step toward developing category learning models that can process relational or predicate structures, Larkey and Love (2003) have developed a model of analogical comparison that is substantially simpler than existing accounts and makes predictions about response time and how task loads that tax working memory affect performance. The model is intended to handle real-world matching problems (e.g., does the current situation match battle plan A or B). As discussed below, the model, Connectionist

Analogy Builder (CAB), is being applied to translating ontologies (representational languages) as part of project headed by Lockheed Martin Advanced Technology Laboratories.

Personnel:

Bradley C. Love, Principal Investigator.

Mathew Jones, postdoctoral researcher (supported by an NRSA fellowship).

John Dennis, Ph.D. student, second year (supported by a University of Texas fellowship).
Todd M. Gureckis, Ph.D. student, fourth and final year (supported by the grant).
Levi Larkey, Ph.D. student, fourth and final year (supported by an NDSEG fellowship).
Yasuaki Sakamoto, Ph.D. student, fifth and final year (supported by the grant).

Publications:

> Love, B. C. (under review, invited paper). Environment and Goals Jointly Direct Category Acquisition. *Current Directions in Psychological Science*.

> Sakamoto, Y., & Love, B. C. (in press) Schematic Influences on Category Learning and Recognition Memory. Journal of Experimental Psychology: General.

> Jones, M. & Love, B. C., (2004). Beyond common features: The role of roles in determining similarity. *Proceedings of the Cognitive Science Society*.

> Sakamoto, Y., & Love, B. C., (2004). Type/Token Information in Category Learning and Recognition. *Proceedings of the Cognitive Science Society*.

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> Love, B. C., & Gureckis, T. M. (in press). Modeling Learning Under the Influence of Culture. In W. Ahn, R. L., Goldstone, B. C., Love, A. B., Markman, & P. Wolff (Eds.), *Categorization inside and outside of the laboratory*. Washington, DC: American Psychological Association.

> Love, B. C., (in press). In vivo or in vitro: Cognitive architectures and task specific models. Book Chapter. D. W. Pew and K. A. Gluck, *Modeling*

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Gureckis, T. M. & Love, B. C. (2002). Who says models can only do what you tell them? Unsupervised category learning data, fits, and predictions. *Proceeding of the Cognitive Science Society*, 399-404.

Yamauchi, T., Love, B. C., & Markman, A. B. (2002). Learning non-linearly separable categories by inference and classification. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 585-593.

Love, B. C. (2002). Similarity and Categorization. *AI Magazine*, 23, 103-105.

Love, B. C. (2001). Three deadly sins of category learning modelers. *Behavioral and Brain Sciences*, 24, 687-688.

Love, B. C. (2001). The Analogical Mind. *Trends in Cognitive Sciences*, 5, 454-455.

Interactions/Transitions:

Bradley Love helped organize a conference to honor Doug Medin that was held last June 2003 at the Chicago Botanical Gardens. Bradley Love gave a talk titled "Modeling the influence of culture on conceptual organization" and is also an editor on an upcoming book (published by the APA) with chapters contributed by the conference's speakers.

Bradley Love has been served on the expert panel for the AMBR project run by the Air Force Research Laboratory under the direction of Dr. Mike Young and Dr. Kevin Gluck. The project involved modeling human category learning under cognitive load in a environment relevant to the Air Force (an air traffic control task). Bradley Love offered input on how the project should be executed and assisted in evaluating the participating teams. He participated in a symposium on AMBR held at last year's Cognitive Science Society conference and contributed a chapter for a book about AMBR that will be published by Erlbaum.

Bradley Love is working to transfer technology to industry. The CAB model of analogical mapping is being considered as a tool for automatic translation of ontologies. Such a tool could allow computer systems that speak different conceptual languages/protocols to communicate effectively. Todd Hughes from Lockheed Martin Advanced Technology Laboratories is heading the effort

Bradley C. Love's work on incorporating decision making into classifiers is currently being used by HRL Laboratories (owned by Boeing, General Motors, and Raytheon). Potential applications include fault detection, medical diagnosis, and efficiently sifting through large amounts of intelligence.

Invited talks:

2/2005	Invited keynote speaker for Lake Ontario Visionary Establishment conference.
6/2004	"Infants, amnesiacs, aging, and the MTL," ASIC 2004, Dolomiti, Italy.

3/2004	"A Clustering Account of Human Learning," AFOSR Perception & Cognition Program Workshop, Phoenix, AZ.
2/2004	"Human Learning, Memory, and the Categories in and Imposed on Our World," UT Odyssey lecture.
1/2004	"A Clustering Account of Human Category Learning," Caltech, Computation and Neural Systems, Pasadena, CA.
11/2003	"Infants, Amnesiacs, and the MTL," ARMADILLO, Texas A&M.
10/2003	"Infants, Amnesiacs, and the MTL," GUV meeting, Chicago, IL.
9/2003	"Category Learning in Infants and Amnesics," J. S. McDonnell Foundation meeting on the cognitive neuroscience of category learning, New York City.
6/2003	"The influence of culture on conceptual organization," Chicago Botanical Gardens, talk given at a conference to honor Douglas Medin.
9/2002	"Two systems or just one," J. S. McDonnell Foundation meeting on the cognitive neuroscience of category learning, New York City.
8/2002	Invited Discussant, AMBR symposium at the Cognitive Science Society Conference, Washington, D.C.
11/2001	"Aging effects in category learning," Harvard University, Mind, Brain, & Behavior Forum Series.

New Discoveries

Bradley C. Love's invention (rights owned by HRL Laboratories) "Incorporating Decision Making into Classifiers" has been granted a patent by the US and European patent offices. Tope-McKay & Associates in Malibu are handling the final paper work.